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Chemical and Physical Characteristics of Rivers Above and Below Four Hydroelectric Power Facilities in the Chiriquí Viejo and Chico Watersheds of Chiriquí, Panama

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Abstract

The advance of anthropogenic climate change and human energy use has sparked unprecedented international interest and investment in fossil fuel free energy sources such as hydroelectric power. Extensive construction of hydroelectric power facilities has occurred in Panama in recent years, particularly in the westernmost Chiriquí province. Hydroelectric power, especially that generated by relatively small facilities, is generally thought to be a "clean" alternative energy source with few negative environmental consequences. Some evidence suggests, however, that even small facilities can have significant ecological impacts on rivers. This study investigated river properties above and below four small hydroelectric facilities on the Chiriquí Viejo, Piedra, Macho Monte, and Piedra/Chico Rivers in Chiriquí, Panama, as well as at 4 sites along the 50 km stretch of the Chiriquí Viejo below one of these facilities. Significant changes in water temperature, pH, concentration of dissolved oxygen, and conductivity were found between sites above and below the Paso Ancho Facility water release on the Chiriquí Viejo River, and significant changes in water temperature and concentration of dissolved oxygen were found above and below the Pedregalito Facility water intake point on the Piedra/Chico River ($p<0.05$). Decreases in water discharge were found below 3 of the 4 hydroelectric facilities studied, with the most extreme example being a 94.99% reduction in water discharge below the Paso Ancho facility's water intake. All of the changes found downstream of the facilities studied can potentially have ecological consequences on these rivers, and this study thus raises concerns regarding the environmental sustainability of continued hydroelectric development in Chiriquí.

Abstracto

El avance de cambio climático y el uso humano de energía ha desatado interés e inversión internacional sin precedentes en fuentes de energía sin combustible fósil como la energía hidroeléctrica. Construcción extensiva de plantas hidroeléctricas ha ocurrido recientemente en Panamá, particularmente en la provincia de Chiriquí. Energía hidroeléctrica, especialmente esa generada por plantas pequeñas, es generalmente considerada como una fuente de energía renovable ambiental con relativamente pocas consecuencias ambientales negativas. Sin embargo, alguna evidencia sugiere que hasta plantas pequeñas pueden tener consecuencias ecológicas significativas en ríos. Este estudio investigó propiedades de ríos antes y después de cuatro plantas hidroeléctricas pequeñas en los Ríos Chiriquí Viejo, Piedra, Macho Monte, y Piedra/Chico en Chiriquí, Panamá, además de en cuatro sitios en el 50 km tramo del Río Chiriquí Viejo después de uno de estas plantas. Cambios significativos en temperatura, pH, concentración de oxígeno disuelto, y conductividad fueron encontrados entre sitios antes y después de la liberación de agua de la Planta Paso Ancho en el Río Chiriquí Viejo, y cambios significativos en temperatura y concentración de oxígeno disuelto fueron encontrados antes y después de la Pedregalito toma de agua en el Río Chiriquí Viejo ($p<0.05$). Reducciones en la descarga de agua fueron encontrados después de 3 de las 4 plantas estudiadas, con el ejemplo más extremo una reducción de 94.99% en la descarga de agua después de la toma de agua de Paso Ancho. Todo los cambios encontrados después de las plantas estudiadas pueden tener consecuencias ecológicas en estos ríos, y esta investigación por consiguiente ocasiona preocupaciones sobre la sostenibilidad ambiental de la continuación del desarrollo hidroeléctrico en Chiriquí.

Acknowledgements

This project would not have been possible without the invaluable assistance of Damaris Sanchez and all of the other members and supporters of FUNDICEPP who helped me along the way. I am also very grateful for Señor Omar, Maria, and Idavelis for taking such good care of me at Hostel Llano Lindo as well as for the support and encouragement of the staff at Hostal Gaia. Lastly, I would like to thank Professor Aly Dagang for her guidance throughout not only my ISP but also my entire time here in Panama.

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Introduction

Hydroelectric Power

The rapid advance of both anthropogenic global climate change and human energy consumption has sparked unprecedented international interest in the development of fossil fuel free energy sources. One such source is hydroelectric power, or the conversion of the potential energy of naturally flowing water to electricity. Hydroelectric power is the largest current source of renewable electricity, contributing 16% of global electricity supply in 2008 (Kumar et al. 2011). Hydroelectric power is an attractive energy source due to its efficiency, reliability, and affordability (Berman 2007). Furthermore, the technical potential for further hydroelectric development around the world is great (Kumar et al. 2011). Hydroelectricity is already a critical source of energy in Central America, accounting for an estimated 5,000 MW in 2011. Moreover, its further expansion is expected by many to promote economic stability and development to the region (Anderson 2013).

Panama is one of several Central American countries that has already and is continuing to invest extensively in hydroelectricity. Hydropower is Panama's largest source of electricity; it accounts for 57.25% of installed electrical capacity and produced 65.84% of electricity generation in 2015 (ASEP 2015). The Panamanian government has heavily incentivized the private sector construction of hydroelectric facilities, particularly "mini" and "small" plants, which in Panama are defined as plants with a generation potential below 10 MW and 20 MW respectively. Under the Legislative Assembly's 2004 Law No. 45, the Establishment of an Incentive Regime for Systems of Hydraulic Generation and of Other New, Renewable and Clean Sources, mini hydroelectric facilities are exempt from transmission and distribution charges. Additionally, both small and mini facilities are allowed to directly contract with distribution utilities and are granted tax exemptions and other fiscal incentives proportional to the amount of CO_2 emissions avoided (Madrigal and Stoft 2012). Many hydroelectric projects in Panama have also received international funding through the Clean Development Mechanism (CDM) (Sempris 2002). The CDM was created under the Kyoto Protocol (1997) and allows for Annex 1, or industrialized, countries to "offset" their own greenhouse gas emissions by financing renewable energy projects in developing countries (Finley-Brook and Thomas 2013).

Despite this extensive investment in and incentivization of hydroelectric development in Panama and around the world, hydroelectric power generating facilities pose a number of ecological risks (Anderson 2013). Until the mid-20th century large hydroelectric projects were viewed as an ideal renewable energy source, but it is now widely acknowledged that they can have major adverse environmental impacts. Some of the main ecological concerns include the flooding of natural environments, fragmentation of riverine habitats, release of potent greenhouse gases, reduced downstream water flow, and disrupted sediment transport (Ledec and Quintero 2003). In recent decades small hydroelectric projects have been heralded by scientists, environmentalists, and politicians as renewable energy sources without the negative consequences of their larger counterparts, but there is no scientific evidence suggesting that smaller plants have fewer adverse environmental impacts per kilowatt of power produced (Premalatha et al. 2014). In fact, studies on small hydroelectric facilities in South Africa, India, and China all documented significant environmental degradation (Mantel et al. 2010, Sinclair 2003, Kibler and Tullos 2013). In some ways smaller projects may actually pose greater environmental risks, for they face less public scrutiny and fewer environmental safeguards on account of their small scale and perceived sustainability (Premalatha et al. 2014). Smaller projects are also more likely to be built in short succession on a single river, and there is evidence suggesting that the ecological effects of successive dams can be particularly significant (Cooper et al. 2016). Thus, while recent development of small hydroelectric facilities in both Panama and internationally has been extensive, the precise environmental repercussions of these facilities are poorly understood.

Dissolved Oxygen

The concentration of dissolved oxygen is an extremely important property of any aquatic ecosystem, for most organisms can only live in specific concentration ranges (Vaquer-Sunyer and Duarte 2012). Hypoxic, or low oxygen, and anoxic, or no oxygen, conditions can be ecologically catastrophic, for very few organisms can survive in oxygen limited environments (Caraco and Cole 2002). Both physical and biological factors influence the concentration of dissolved oxygen in an ecosystem. Oxygen is more soluble and therefore present in higher concentrations in colder water and at lower elevations (Welch et al. 2001). Increased exposure to the atmosphere can also increase dissolved oxygen concentrations, with turbulent waters typically having dissolved oxygen concentrations near saturation (Welch et al. 2001). Photosynthesis (Equation 1) undergone by autotrophic organisms adds oxygen to the surrounding environment while cellular respiration by heterotrophic organisms and decomposition (Equation 2) consume oxygen (White 2008).

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \text{(Equation 1)}$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad \text{(Equation 2)}$$

Given this complexity, there are a number of ways in which hydroelectric facilities may change the concentration of dissolved oxygen in the water released back to the river. Cellular respiration and decomposition in deep water storage reservoirs above large facilities can result in hypoxic waters in the deeper layers of the reservoir (De Oliviera 2009). Stratification, or the separation of water layers based on differences in chemical and physical properties, minimizes the mixing that can occur between oxygen rich top layers and oxygen depleted bottom layers (Turner and Erskine 2005). This can then result in the return of oxygen depleted waters from deep in the reservoir back to the river below the facility, as was the case below several large hydroelectric facilities on tropical rivers in Brazil (De Oliviera 2009). Meanwhile, the lentic, or slow-flowing, nature of hydroelectric facility reservoirs can encourage the growth of phytoplankton (Sow et al. 2016). Since photosynthesis produces oxygen, this can result in the supersaturation of oxygen in reservoirs and thus in the water returned to the river downstream of the facility (Osborne 2000).

Temperature

Most freshwater organisms also require certain temperature ranges to survive, and temperature plays an important role in determining organism growth and development (Poff and Hart 2002). Temperature helps determine other water properties such as density and affects the solubility of gases such as oxygen as well as other molecules and compounds (Osborne 2002). River temperature is a function of many factors such as river depth, velocity, solar radiation, and air temperature (Webb et al. 2008). Temperatures in most rivers vary on daily and and seasonal timescales, and these thermal fluctuations can strongly influence river productivity (Caissie 2006).

Hydroelectric facilities are often linked to downstream changes in river water temperature dynamics (Osborne 2002). Larger facility reservoirs become stratified with regards to temperature, as with dissolved oxygen concentration. Deeper water layers can be much colder than surface waters, and when water release valves are located near the bottom of the reservoirs this can result in the return of uncharacteristically cool water back to the river (Poff and Hart

2002). For instance, water temperature was lower below a large hydroelectric facility in Spain during the Winter, Spring, and Summer (Pratts et al. 2012). Meanwhile, the water released from the surface of smaller water reservoirs can be warmer than that above the facility's influence (Lessard and Hayes 2003). In addition to causing increases or decreases in temperature, hydroelectric facilities can mute or even eliminate natural temperature fluctuations (Poff and Hart 2002). Downstream of a hydroelectric facility in Argentina, for example, water temperature was less closely linked to climatic variation, and diurnal fluctuation in river temperature was smaller in magnitude and delayed in timing relative to upstream locations (Casado et al. 2013).

pH

pH is a logarithmic scale measurement of the concentration of hydronium ions present in a solution, with a lower value corresponding to a more acidic solution. pH is sometimes referred to as the master variable of aquatic ecosystems, for it affects the rate of chemical weathering and many other chemical processes (White 2013). Like dissolved oxygen concentration, pH can be affected by a number of factors. While there are a number of species that exist in equilibrium with hydronium in rivers, river pH is primarily a reflection of carbonate speciation (Equation 3).

$$\boldsymbol{CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}} \qquad \text{(Equation 3)}$$

Because carbon dioxide exists in equilibrium with carbonic acid, bicarbonate ions, and carbonate ions in solution, higher carbon dioxide availability corresponds with more acidic, lower pH waters (White 2013). Thus, geological and biological sources and sinks of carbon dioxide to rivers affect their acidity. The weathering of bedrock can be a significant source of carbonate to rivers and thus lower pH, but under other geological conditions bedrock weathering can make waters more basic (Bookter 2008). Photosynthesis consumes carbon dioxide and therefore increases pH, while cellular respiration and decomposition produce carbon dioxide and therefore lower pH (Semesi et al. 2009).

Due to the relationship between pH and biological activity, pH can become stratified with depth in hydroelectric facility reservoirs. Surface waters become more basic due to the photosynthesis they support, and cellular respiration and decomposition in lower waters results in more acidic conditions (Osborne et al. 2002). Lower pH was found downstream of a hydroelectric facility in China, and the authors attributed this change to diatom decomposition and respiration at depth in the facility reservoir (Gao et al. 2013). A study of another facility in China also found downstream decreases in pH and used isotopic carbon analyses to confirm that pH was stratified with depth in the reservoir due photosynthesis/cellular respiration dynamics (Wang et al. 2014).

Conductivity

Conductivity is a measure of the ability of a solution to carry an electrical current, and is thus a proxy for the concentration of dissolved ions in a solution (Welch et al. 2001). Dissolved ions, particularly the major cations and anions Ca^{2+}, Mg^{2+}, Na^+, HCO_3^-, Cl^-, and SO_4^{2-}, are naturally present in rivers due to bedrock weathering and terrestrial runoff, and they can also be added to rivers from anthropogenic sources (Welch et al. 2001). The concentration and composition of dissolved ions present in a given section of a river strongly influences the algal community and therefore the entire ecosystem it can support (Potapova and Charles 2003). Some spatial variability in water conductivity is expected in rivers; for example, conductivity naturally increases moving downstream in a river, for as the water moves to lower elevations it has more time to weather bedrock (Welch et al. 2001). Changes in conductivity can reflect changes in other chemical and biological water properties. For instance, one study found a positive correlation between conductivity and nitrate concentration and denitrification rate (García-Ruiz et al. 1998). Higher conductivity is also linked to periods of lower river flow, since dissolved ion concentrations are less diluted (Jesus et al. 2004). Hydroelectric facility development can disrupt the natural cycling of dissolved ions, and thus the water conductivity, of rivers. For instance, conductivity was found to have reduced annual variability downstream of a hydroelectric facility in Spain (Camargo and Jalon 1990).

Turbidity

Turbidity, or the ability of a water sample to permit or prohibit the passing of light, is another key river property. Turbidity determines light availability, so it affects the phytoplankton and therefore entire biological community of a river (Henley et al. 2000). Moreover, turbidity is a result of suspended particles in a water sample, so it can serve as a proxy for sediment transport (Rugner et al. 2013). Sediment transport is a primary function of rivers, for the sediment that rivers carry replaces sediment in banks and estuaries as it eroded away by the river's flow (Osborne 2000).

Anthropogenic river regulation often reduces the amount of sediment that rivers transport, for sedimentation, or the settling out of particles previously suspended in the water column, can occur in facility reservoirs (Govorushko and Rupert 2012). The decrease in sediment transport caused by damming and reservoir creation have affected surface earth processes on a global scale (Rosenberg et al. 2000). In a particularly extreme example, the construction of dams and reservoirs has contributed to a 50% decrease in the sediment load carried to the Gulf of Mexico by the Mississippi River (Meade 1995). Reservoir sedimentation is generally proportional to the water residence time of a facility's reservoir or reservoir, but other factors such as the reservoir topography can result is significant sedimentation even in small reservoirs with relatively short water residence times. (Verstraeten and Poesen 2000). The sedimentation of suspended particulate matter occurred when reservoir water residence times were under one day at a small facility in South West France (Sow et al. 2016). Dams also effect the ratio of coarse-to-fine sediment rivers carry, since the sedimentation of larger particles occurs more rapidly in reservoirs (Osborne 2000).

Phosphate Concentration

Phosphate is one of the key nutrients limiting primary productivity in aquatic ecosystems (Correll 1999). Since phytoplankton consume phosphate, low concentrations can be an indicator of large upstream phytoplankton communities. The lentic conditions of hydroelectric facility reservoirs can be conducive to phytoplankton growth, as is discussed above. This phytoplankton growth removes nutrients such as phosphate from the water column and results in the return of nutrient depleted water to the river below the facility (Sow et al. 2016). Given that nutrient availability is a primary control on primary productivity and that phytoplankton form the base of riverine food webs, this nutrient depletion can have ecological repercussions downstream (Likens 2010). Conventional wisdom may suggest that long reservoir water residence times are necessary for phytoplankton proliferation to cause a decrease in water column phosphate availability, but phosphate concentrations decreased by 24% downstream of a small, run-of-the-river hydroelectric facility in South West France. Seasonal trends and testing of chlorophyll *a* strongly suggested that this decrease was driven by phytoplankton primary productivity (Sow et al. 2016). A study on two hydroelectric facilities in California, however, found that reservoirs can be a net phosphate source during unusually dry years (Ahearn 2005).

River Velocity, Cross-sectional Area, and Discharge

The size, velocity, and discharge, or the amount of water a river transports, are likely the most fundamental properties of any river. The depth, width, and velocity of a river all help determine what biological activity it can support, and river discharge determines the quantity of water available downstream for both biological and human use (Osborne 2000). River discharge (D) is the product of the cross-sectional area (A) and velocity (V) of a river at a particular point (Equation 4) (Gierke 2002).

$$\boldsymbol{D} = \boldsymbol{V} \times \boldsymbol{A} \qquad \text{(Equation 4)}$$

Decreases in water discharge are a common concern in hydroelectric facility construction, particularly where the facility water intake is a significant distance from the location where water is returned back to the river (Govorushko and Rupert 2012). Scientific literature suggests that adverse environmental impacts can occur below any facility in which river discharge is below 75% of unrestricted conditions, but it can be very difficult for small facilities in particular to be economically viable while only diverting 25% of river flow (Premalatha et al. 2014). Under Panama's National Authority of the Environment (ANAM) Resolution 0691-2012 hydroelectric facilities are only required to maintain a downstream discharge of 10% of the river's unregulated average annual flow (Gobierno 2012). Moreover, river discharge downstream of hydroelectric facilities can either fluctuate unnaturally or be unusually stable depending on the facility's operation mode, and both cases can decrease downstream biodiversity (Ahearn et al. 2005). For instance, the lack of periodic storm flow surges that river regulation brings can cause silt to accumulate in downstream river beds and bars and thus damage fish spawning habitat (Ahearn et al. 2005). Moreover, the muting of seasonal and yearly variation in river discharge that can result from dam construction creates a distinct hydrological regime below the facility (Osborne 2000).

Study Specifics

In light of the scarcity of scientific knowledge on the subject, this study investigated small and mini hydroelectric facilities in Chiriquí, Panama, the province at the center of Panama's recent hydroelectric development. Construction on 21 new hydroelectric facilities began in Chiriquí since 2007 alone (ASEP 2016). Water properties were tested directly above and below four facilities, Paso Ancho, Pedregalito I, RP-550, and La Cuchilla, as well as at 4 more locations further downstream of Paso Ancho in order to obtain a more holistic understanding Chiriquí Viejo river dynamics.

According to Panama's designation scheme, Pedregalito I is a "small" facility and the 3 others are "mini" facilities (Table 1). The functionality of Pedregalito I is paired with that of Pedregalito II, another hydroelectric facility 0.35 km downstream from it. The portion of the Chiriquí Viejo where additional testing was done supports 5 larger facilities: Pando, Monte Lirio, Bajo de Mina, Bajo Frio, and El Alto. All facilities under the scope of this investigation are currently in operation with the exception of La Cuchilla, which is under construction and is expected to commence operation in October 2017 (ASEP 2016). While the specific construction of these facilities vary, most are "run-of-the-river" type facilities in which the river is dammed to create a pondage, or relatively small water storage reservoir, and a portion of the water is diverted to turbines located some distance away from the river (Sow et al. 2016). Once the water flow has been converted to electrical energy the water is returned to the river at a water release downstream (Govorushko and Rupert 2012).

Table 1. Location and installed power generation capacity of the 7 hydroelectric facilities within the scope of this investigation (ARHSA 2014, ASEP 2016, INGEMAR 2016, INCISA 2016, Ramos and Muñoz 2011, Ramos 2011).

Facility	Watershed	River	Capacity, MW
RP-550 (Macano II)	Chico (106)	Piedra	4.15
Paso Ancho	Chiriquí Viejo (102)	Chiriquí Viejo	7
La Cuchilla	Chico (106)	Macho Monte	7.62
Pedregalito II	Chico (106)	Piedra/Chico	14
Pedregalito I	Chico (106)	Piedra/Chico	20
Pando	Chiriquí Viejo (102)	Chiriquí Viejo	32.6
Monte Lirio	Chiriquí Viejo (102)	Chiriquí Viejo	50.4
Bajo de Mina	Chiriquí Viejo (102)	Chiriquí Viejo	56.8
Bajo Frío	Chiriquí Viejo (102)	Chiriquí Viejo	58
El Alto	Chiriquí Viejo (102)	Chiriquí Viejo	77

The Chiriquí Viejo River begins in La Amistad International Park in the La Amistad UNESCO Biosphere near the town of Cerro Punta in Chiriquí, Panama. It runs west before curving and running south along the western edge of the country for a total distance of 161 km. It is the principle river of the Chiriquí Viejo Watershed (102), which covers an area of 1376 km^2 (ETESA 2009). The upper portion of the river runs through steep canyons, while the lower portion runs through alluvial plains before reaching mangroves at its mouth in the Gulf of Chiriquí (IDB 2009). As of 2013, the Chiriquí Viejo river alone supported 33% of Panama's hydroelectric concessions, with 13 concessions granted and 7 more pending (IDB 2013). Water from the river is used for both human consumption and agriculture, and its middle section is considered a top white water rafting destination (IDB 2009).

The other 3 rivers sampled, Piedra, Macho Monte, and Chico, are all within the neighboring Chico Watershed (106), which has a total area of 593.3 km^2 (ETESA 2009). The Piedra River is the principle river of the watershed and runs 72 km south through alluvial plains in central Chiriquí before draining into the Gulf of Chiriquí (Gutierrez 1987). Macho Monte and Chico are tributaries of the Piedra River, with lengths of 27 km and 22 km respectively (Gutierrez 1987). The Piedra River is sometimes referred to as the Chico River below its convergence with the Chico, so this lower portion is referred to as the Piedra/Chico River in this report.

Both watersheds, like most of the province of Chiriquí, are largely agricultural (INEC 2011). In accordance with its tropical location, Chiriquí has a distinct wet season (May-November) and dry season (December-April). This precipitation seasonality causes significant seasonal changes in river size, discharge, and chemistry throughout the tropics (Lewis 2008). Moreover, the very strong 2014-2016 El Niño Southern Oscillation (ENSO) event is just concluding, and the low precipitation conditions ENSO brings tropical regions can have a large effect on river conditions (CPC 2016; Amarasekera 1996). Chiriquí is home to neotropical river otters as well as a number of migratory fish species, all of which rely on unrestricted movement through its river system to carry out their full life cycles (IDB 2009). Both the Chiriquí Viejo and Chico watersheds already support many hydroelectric facilities of various sizes. The hydroelectric developments on these watersheds, as well as those elsewhere in the province and country, have been subject to considerable community opposition. For instance, in January 2010, 16 local organizations submitted a complaint to the International Finance Corporation (IFC) concerning the environmental and social impacts of the Chiriquí Viejo Pando Monte Lirio hydroelectric development it financed (IFC 2010). Despite this community opposition, multiple concessions for future hydroelectric facility construction in both watersheds have been granted and new construction projects continue to be planned (ASEP 2016).

Research Question

Do the chemical and physical characteristics of rivers in Chiriquí, Panama change as they pass through the hydroelectric facilities they support, and, if so, how?

Methods and Materials

This project consisted of 3 and 5 days of data sampling above and below the Pedregalito and Paso Ancho hydroelectric facilities respectively, one-time sampling above and below the La Cuchilla and RP-550 hydroelectric facilities, and one-time sampling of 4 sites geographically distributed along the Chiriquí Viejo River (Figure 1). Testing was performed above and below both the water intake and the water release point for the Paso Ancho facility, but all other observations were collected above and below only the water intake points. Upstream testing was performed as close as possible to the start of each facility’s above-dam reservoir, and downstream testing was performed as close to the dam as possible. Chiriquí Viejo sampling locations were selected according to accessibility. All observations were collected between April 15 and April 30, 2016, at the end of Panama’s dry season. The repeated testing performed at the Paso Ancho and Pedregalito locations was performed at various times of the day over the course of the two-week field work period. Testing at the downstream site was always conducted within 1 hour of testing at the upstream site.

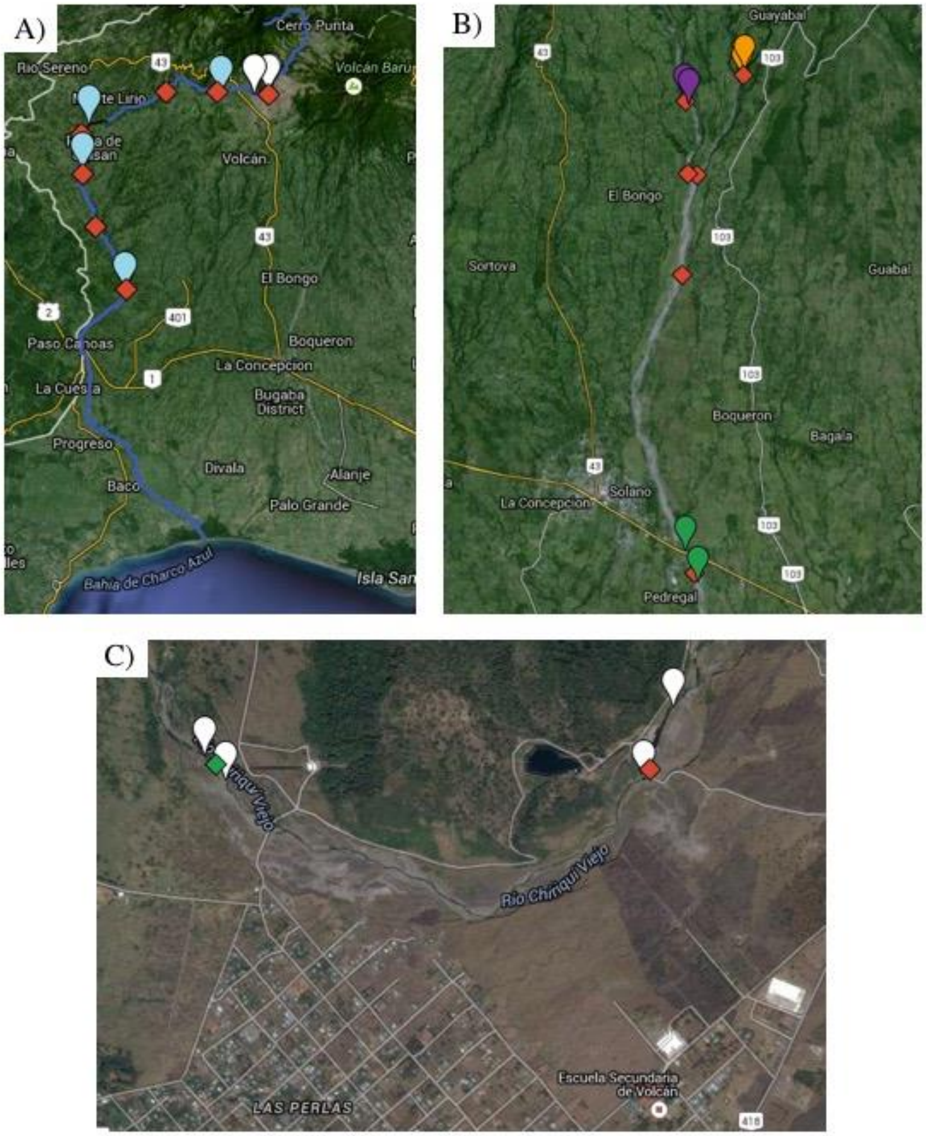

Figure 1. A) Study sites along the Chiriquí Viejo River, including both sites visited once (blue pins) and the sites visited repeatedly for the Paso Ancho subproject (white pins). Hydroelectric facilities are marked with red diamonds, and the length of the Chiriquí Viejo River is outlined in blue. B) Study sites (white pins) above and below the water intake point (red diamond) and above and below the water release point (green diamond) for the Paso Ancho Hydroelectric facility. C) Study sites above and below the RP-550, La Cuchilla, and Pedregalito hydroelectric facilities, marked with orange, purple, and green pins respectively. All hydroelectric facilities in the region are marked with red diamonds.

Each round of sampling consisted of measuring dissolved oxygen, pH, water temperature, conductivity, and water velocity. Dissolved oxygen concentration was tested using a SPER Scientific Model 850045 DO Pen and pH was tested using an ecoTester pH2 Probe. Both instruments were calibrated according to manufacturer instructions prior to use, with LaMotte TesTabs of pH 4.0, 7.0, and 10.0 used to calibrate the pH probe. Water temperature was tested using a handheld thermometer, and conductivity was measured using an Extech ExStikII Conductivity/TDS/Salinity Probe. All four measurements were conducted at least 1 m in from the river's edge and repeated three times at 10 minute intervals. Turbidity was measured using a Water Monitoring Equipment and Supply brand turbidity tube. Additionally, a CHEMetrics Phosphate K-8510 test kit was used to test dissolved phosphate concentration at only the Pedregalito and Paso Ancho test sites. Phosphate testing was performed once at each location.

The surface water velocity for all sites except Bajo de Mina and Monte Lirio was determined by the "float method," in which a straight, obstacle-free stretch of river with relatively constant width and depth is identified and the time it takes an object to float 5 m downstream was recorded (Gierke 2002). The surface velocity value obtained through this measurement was multiplied by a factor of 0.85 to yield an estimate for average river velocity (Dingman 2002). River width and depth were determined during the first visit to each site. River width was determined using a range finder for sites with a width greater than 5 m and a tape measure for sites with a width less than 5 m. River depth was measured using a tape measure at 5 points equidistantly spaced across the river width (Sauer and Meyer 1992). Average river depth was calculated by averaging these 5 values, and cross-sectional area was determined by multiplying width by this average depth value. River discharge was then calculated by multiplying average river velocity by cross-sectional area (Gierke 2002). The UTM coordinates of each study site was determined using a Garmin eTrex20x GPS unit, and all sites were photographed immediately following data collection.

Results

Paso Ancho Hydroelectric Facility

Five field days were conducted at both the water intake and water release points for the Paso Ancho hydroelectric facility. Testing was performed 160 m above (CV1) and 10 m below (CV2) the water intake point and 20 m above (CV3) and 10 m below (CV4) the water release point, which is 2.1 m downstream from the water intake (Figure 2). pH was significantly higher at CV2 than at CV1 ($p<0.05$), but dissolved oxygen, temperature, and conductivity did not vary significantly above and below the water intake (Figure 3). Both surface water velocity and river discharge were lower below the water intake point ($p<0.05$ and $p<0.01$ respectively, Figure 3). Average river discharge at CV2, 0.16 m^3/sec, was only 5.01% of the average discharge at CV1. The concentration of dissolved oxygen was higher at CV4 than at CV3 ($p<0.05$), while temperature, pH, and conductivity were all lower at CV4 than CV3 ($p<0.01$, $p<0.01$, and $p<0.05$, respectively, Figure 3). Both surface water velocity and river discharge were significantly higher below the water release ($p<0.05$, Figure 3).

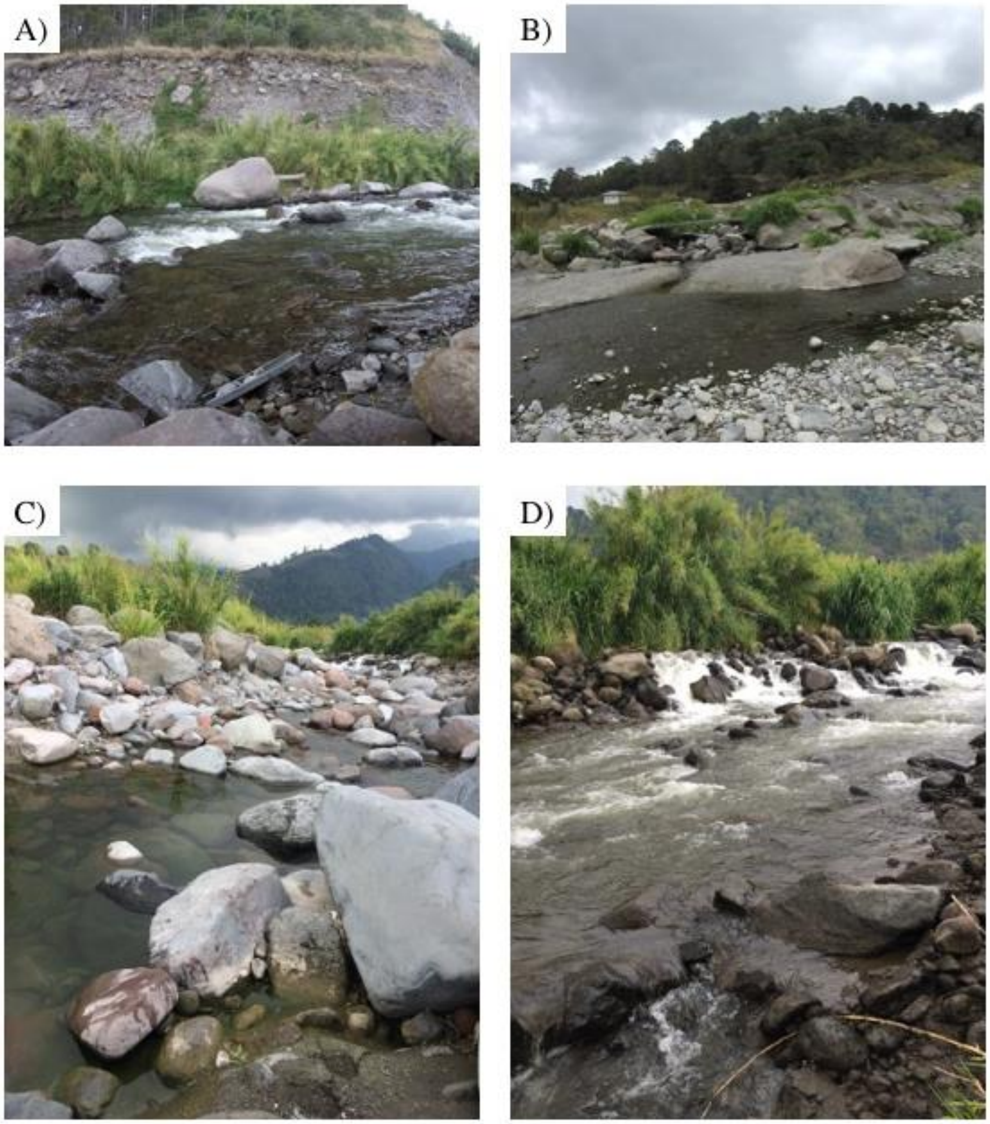

Figure 2. Photographs of study sites CV1, CV2, CV3, and CV4.

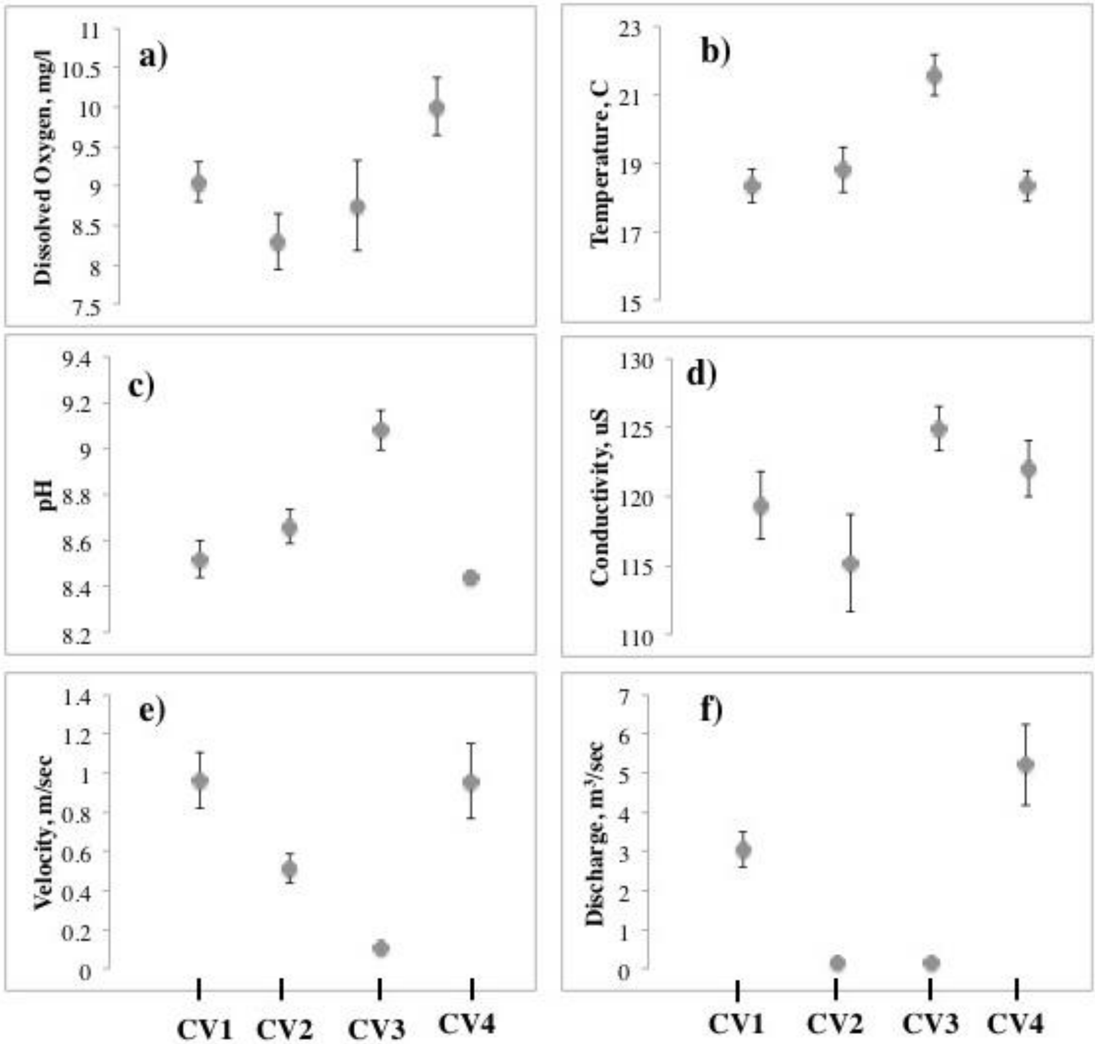

Figure 3. Average a) dissolved oxygen concentration, b) temperature, c) pH, d) conductivity, e) surface water velocity, and f) river discharge across 5 days of sampling at sample sites 160 m above (CV1) and 10 m below (CV2) the water intake point and 20 m above (CV3) and 10 m below (CV4) the water release point of the Paso Ancho hydroelectric facility. Error bars depict calculated standard error in each measurement.

Variability in surface water velocity below the water release was particularly large, with velocity ranging from a maximum of 1.8 m/sec to a minimum of 0.46 m/sec. Of the 6 characteristics, only dissolved oxygen and river discharge varied significantly between study sites CV1 and CV2 ($p<0.05$). Colorimetric phosphate concentration testing was conducted once at each site, and the concentration at sites CV1, CV2, and CV4 was found to be 0.4 ppm while the concentration at site CV3 was 0.6 ppm. Sites CV2 and CV3 were considerably shallower and narrower than sites CV1 and CV2 (Table 2).

Table 2. Average river depth and width at sites CV1, CV2, CV3, and CV4.

	Average depth (cm)	Width (m)
CV1	33	11
CV2	13	2.8
CV3	32.6	5.4
CV4	65	10

Chiriquí Viejo River Sampling

In addition to the repeated sampling of the 4 Paso Ancho Chiriquí Viejo River sampling locations, one-time sampling was performed at 4 locations below the Paso Ancho test sites 24.03, 50.17, 58.61, and 68.13 km downstream from the river's beginning. The river was freely flowing at the first and last of these additional sites, but observations were collected on the stagnant river reservoirs immediately above hydroelectric facilities for the middle two sites. The first additional site had an average depth of 35 cm and a width of 14 m, and the last had an average depth of 74 cm and a width of 21 m. The second and third reservoir sites had widths of 51 m and 140 m respectively. Depth measurements could not be taken at these sites due to practical restraints.

The first additional Chiriquí Viejo site was the only location among all 14 sites visited with water turbidity above the detection limit of the turbidity tube used, with a Secchi Disk depth of 10.4 cm. There was no apparent trend in the concentration of dissolved oxygen or pH over the length of the river, but there was a slight downstream increase in temperature and conductivity (Figure 4). No downstream trend in surface water velocity or river discharge was apparent in the data, for while the lowermost site has the highest velocity, 1.8 m/sec, and discharge, 7.5 m^3/sec, of all sites sampled, the water was stagnant at the middle two additional sites (Figure 4).

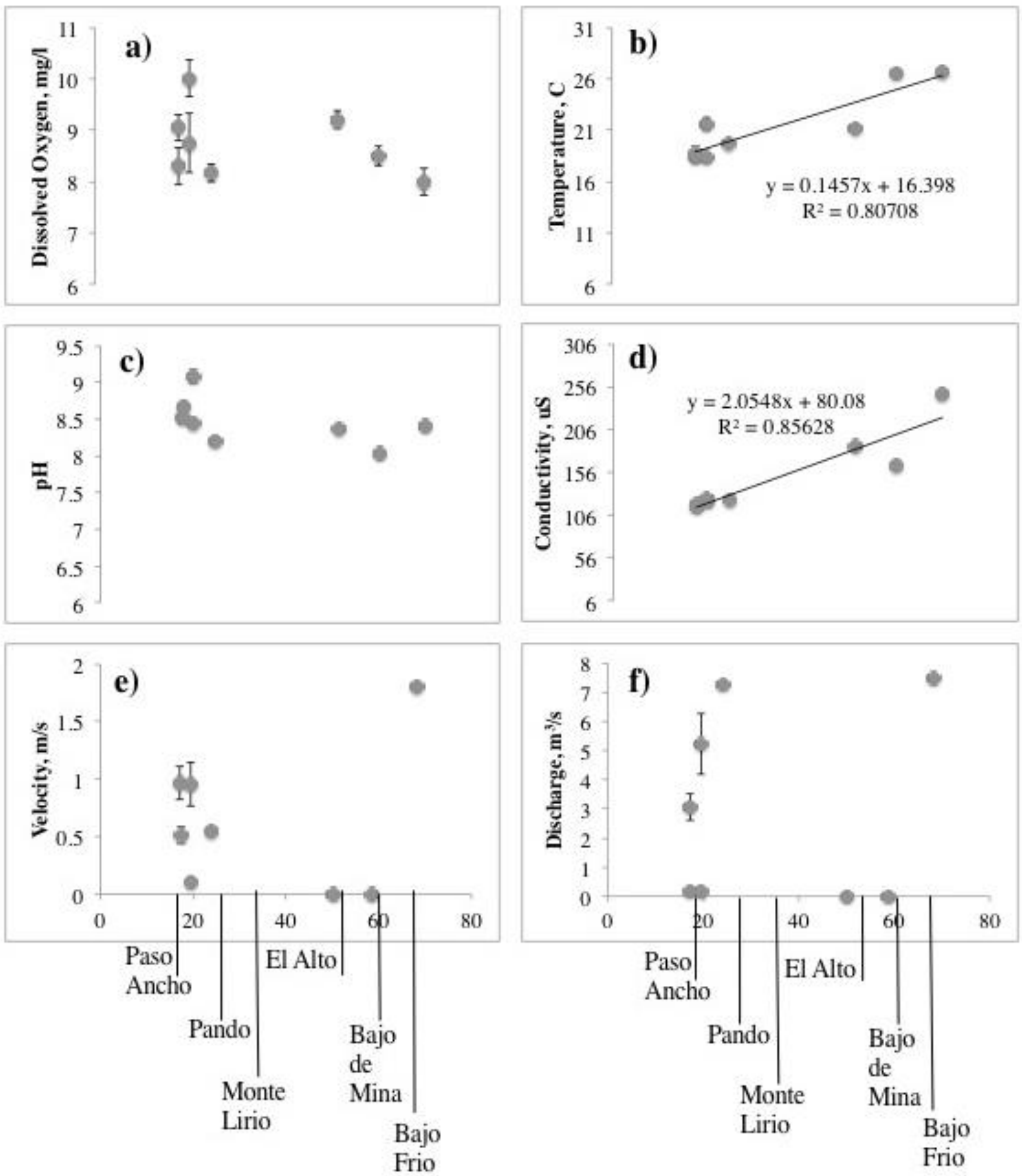

Figure 4. Average a) dissolved oxygen concentration, b) temperature, c) pH, d) conductivity, e) surface water velocity, and f) river discharge across all Chiriquí Viejo sampling locations plotted against distance downstream from the river's beginning. The locations of all hydroelectric facilities present in the study region are marked. Error bars depict standard error for all data points with the exception of velocity and discharge for the 4 lowermost locations, for which only one measurement was collected.

Pedregalito Hydroelectric Facility

Three field days were conducted at the Pedregalito hydroelectric facility, with observations taken 800 m above and 325 below the dam and water intake point. The upstream and downstream sites appeared notably different, with the river being visibly wider and calmer below the hydroelectric facility (Figure 5). The concentration of dissolved oxygen was significantly higher below the facility on 2 of the 3 days of sampling, 4/23/16 and 4/27/16 (p<0.05, Figure 6). Temperature was significantly lower below the facility on all 3 days of testing (p<0.05, Figure 6).

Figure 5. Photographs of the two Pedregalito test sites: a) the upstream test site 800 m above and b) the downstream test site 325 m below the Pedregalito hydroelectric facility, as well as c) a photograph of the reservoir directly above the facility.

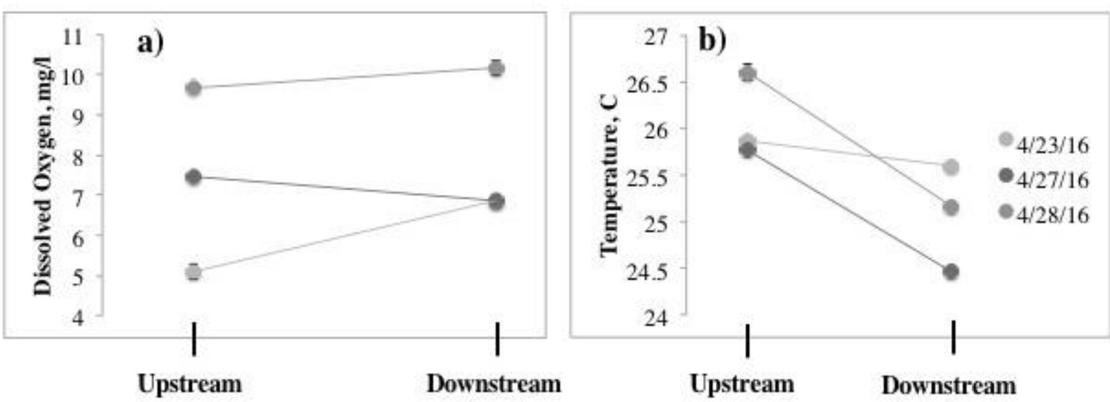

Figure 6. Average a) dissolved oxygen concentration and b) water temperature on each of 3 days of sampling 800 m above and 325 m below the Pedregalito hydroelectric facility.

One-time colorimetric testing revealed a decrease in the concentration of phosphate below the hydroelectric facility, with a concentration of 0.2 ppm at the upstream testing location and 0.4 ppm at the downstream location. pH, conductivity, and river discharge did not vary significantly between the 2 locations on any day of measurement, but the downstream site was both deeper and wider (Table 3). Average surface water velocity across the 3 days of sampling was significantly lower below the facility than above it ($p<0.05$, Figure 7).

Table 3. Average pH, conductivity, and river discharge across 3 days of sampling as well as average depth and width 800 m upstream and 325 m downstream of the Pedregalito hydroelectric facility.

	Upstream Site	Downstream Site
pH	8.48 ± 0.04	8.41 ± 0.03
Conductivity (µS)	114 ± 2	110 ± 5
Discharge (m^3/sec)	2.7 ± 0.2	3.6 ± 0.2
Average depth (cm)	12	24
Width, (m)	21	34

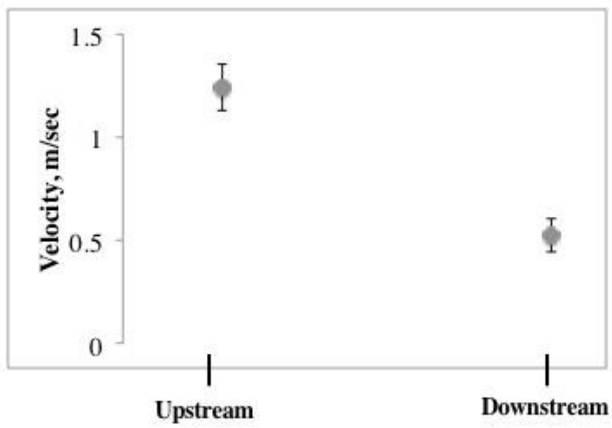

Figure 7. Average surface water velocity over the 3 days of sampling 800 m upstream and 325 m downstream of the Pedregalito hydroelectric facility.

RP-550 Hydroelectric Facility

One-time testing was performed 170 m above and 110 m below the RP-550 hydroelectric facility. Dissolved oxygen, pH, temperature, and conductivity did not differ significantly between the upstream and downstream sites, but the downstream site was both narrower and shallower (Table 4). Surface water velocity was higher and river discharge was lower below the facility (Figure 8).

Table 4. Average dissolved oxygen, pH, temperature, and conductivity as well as average depth and river width 170 m above and 110 m below the RP-550 hydroelectric facility.

	Upstream Site	Downstream Site
Dissolved Oxygen (mg/l)	8.3 ± 0.1	8.3 ± 0.2
pH	8.3 ± 0.1	8.1 ± 0.1
Temperature (°C)	23.4 ± 0.1	23.4 ± 0.1
Conductivity (µS)	107.7 ± 0.4	108 ± 0.2
Average Depth (cm)	20	11
Width (m)	16	12

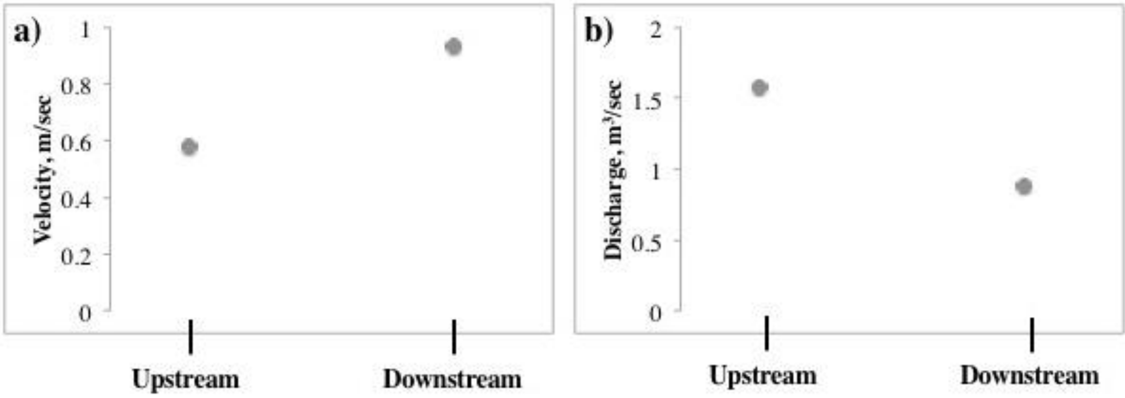

Figure 8. Surface water velocity and river discharge 150 m above and 90 m below the RP-550 hydroelectric facility.

La Cuchilla Hydroelectric Facility

One-time testing was performed 65 m above and 130 m below the construction site of the La Cuchilla hydroelectric facility. Dissolved oxygen, pH, conductivity, and surface water velocity did not differ significantly between the upstream and downstream sites (Table 5). The river was both shallower and narrower at the downstream location (Table 5). Temperature and river discharge did differ between the two sampling sites. Average water temperature was significantly higher at the downstream location, and the one-time calculated river discharge was lower below the facility ($p<0.01$, Figure 9).

Table 5. Average dissolved oxygen, pH, and conductivity as well as one-time measurements for surface water velocity, average depth, and river width 65 above and 130 below the construction site of the La Cuchilla hydroelectric facility.

	Upstream Site	Downstream Site
Dissolved Oxygen (mg/l)	9.6 ± 0.1	9.6 ± 0.1
pH	8.5 ± 0.1	8.5 ± 0.1
Conductivity (μS)	138 ± 1	138 ± 1
Surface Water Velocity (m/sec)	0.35	0.50
Average depth (cm)	83	41
Width (m)	12	7

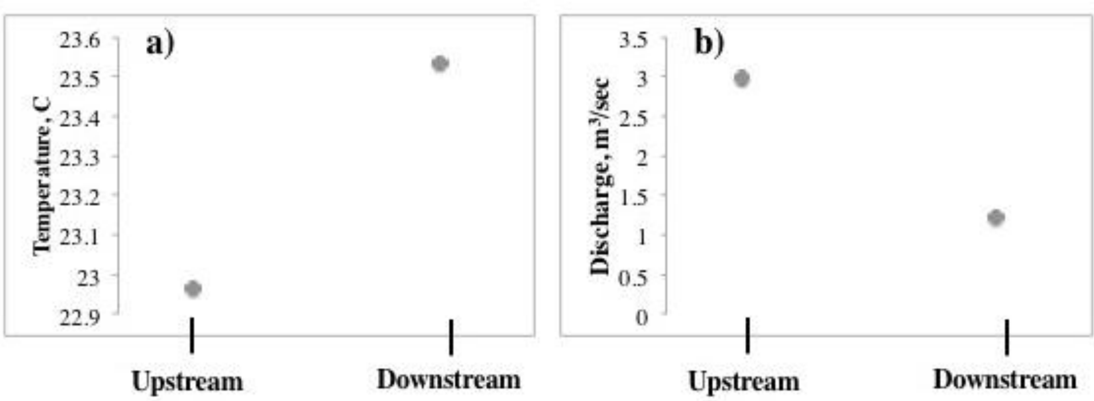

Figure 9. Temperature and river discharge 65 m above and 130 m below the La Cuchilla hydroelectric facility.

Discussion

Changes downstream of hydroelectric facilities

There were changes in the physical and chemical properties of the rivers above and below all four hydroelectric facilities tested. While these precise changes were distinctive to each location, some trends were present at multiple facilities. For instance, river discharge was significantly lower below the hydroelectric facility at all locations with the exception of Pedregalito. Since river discharge is a measure of how much water a river transports, these decreases mean that less water is available downstream of each of these facilities for both biological activity and human usage (Govorushko and Rupert 2012). It is of particular interest to note that average water discharge immediately below the water intake point for the Paso Ancho facility was only 5.01% of that at the upstream location. This value is not only well below the 75% flow recommended to preserve ecological stability but is also lower than the 10% flow required by Panamanian law (Premalatha et al. 2014, Gobierno 2012). Average river discharge below the Paso Ancho water release was higher than that before the facility's intake, but the fact remains that the discharge was extremely low for the 2.1 km between the intake and release.

Water discharge below the Paso Ancho water release point was also quite variable on account of fluctuation in water velocity between the 5 days of testing. This daily fluctuation in river flow is a common issue cited in literature surrounding hydroelectric facilities (Ahearn et al. 2005). Flow fluctuations can compound the ecological issues caused by changes in water discharge, for organisms must be able to survive not only in lower flow conditions but also constantly changing conditions (Bunn and Arthington 2000). Water velocity also changed downstream of all locations, decreasing below the Pedregalito facility and the Paso Ancho intake and increasing below all other locations. Most riverine organisms can only survive within a certain range of water velocity, so these changes are also likely to have ecological impacts (Bunn and Arthington 2000).

The other properties tested did not change uniformly across all sites, but their variances are noteworthy nonetheless. A decrease in water temperature was found below the Pedregalito intake and the Paso Ancho water release. Such decreases in temperature are common below hydroelectric facilities since water can cool as it is kept at depth in facility reservoirs (Poff and Hart 2002). It is unclear, however, if this was the case at the Paso Ancho facility, for the water temperature at site CV4 is comparable to the temperature above the facility while the average temperature of CV3 is 3.2°C higher. Therefore, it is possible that unusual cooling does not occur in the water diverted for facility use but rather that unusual warming occurs in the 2.1 km stretch proceeding CV3 due to its particularly shallow nature. At the same time, warming along the length of a river is to be expected, so CV4 may in fact be anomalously cool (Welch et al. 2001). In any case, even the small changes in water temperature observed in this study can have ecological repercussions (Poff and Hart 2002).

The concentration of dissolved oxygen was higher below both the Pedregalito water intake and the Paso Ancho water release. The average temperature of both of the sites was below that of the proceeding ones, so this increase in oxygen concentration can be partly attributed to an increase in oxygen solubility in downstream waters. In both cases, however, the decrease in temperature cannot entirely account for the extent of the increase in concentration. Dissolved oxygen may be added to the river's water column through the physical agitation that occurs as the river water passes through the hydroelectric facility (Welch et al. 2001). The increase may also be partly due to an increase in oxygen production due to primary productivity in the facility reservoirs since photosynthesis produces oxygen (Osborne 2000). This explanation is supported by the decrease in phosphate concentration below the Pedregalito water intake, for phytoplankton consume nutrients such as phosphate in addition to oxygen (Sow et al. 2016). Phosphate concentration increased below the Paso Ancho facility however, which does not support this hypothesis. In any case, phosphate concentration was only tested once at each site and differences in concentration were small, so the results should be analyzed with caution. An increase in reservoir primary productivity is also supported by the slight decrease in conductivity present below the Paso Ancho water release, for phytoplankton consume various dissolved ions (Potapova and Charles 2003).

The pH immediately above the Paso Ancho water release was higher than not only any other Paso Ancho site but also all of the Chiriquí Viejo sites sampled. It is unlikely that this change is due to a variance in bedrock composition given the geographic proximity of the study sites. Bedrock weathering may play a role in the change, however, for the low water flow in this portion means that any geologic contributions to the river that affect pH will be less diluted (Jesus et al. 2004). This increase may also suggest that there were high rates of primary productivity in the stretch of river below the water intake, since photosynthesis consumes carbon dioxide and thus increases pH (Semesi et al. 2009). This is in contradiction to the previously stated conjecture of higher reservoir primary productivity to explain downstream trends in dissolved oxygen, phosphate, and conductivity, however. Thus, further testing such as chlorophyll *a* analyses would be necessary to make conclusions regarding the primary productivity dynamics of this stretch of river. In any case, the anomalous pH and temperature of site CV3 strongly suggest that the low flow conditions in the 2.1 km interval between the Paso Ancho water intake and release affect the river's chemical and physical properties.

Due to the low sensitivity of the turbidity testing method used, very little turbidity information could be gathered. The only conclusions that can be drawn regarding turbidity is that turbidity at the first additional Chiriquí Viejo site was higher than that of all other sites sampled, and that all other sites have a Secchi Disk depth of greater than 60 cm. This low turbidity reflects a relatively low sediment load, which may be due to either the natural composition of these rivers or the extensive hydroelectric development they support. Sediment transport has been found to be lower downstream of hydroelectric facilities in various contexts, and this decrease in sediment transport can cause problematic erosion of river banks and estuaries (Osborne 2000). More accurate turbidity testing would be required to determine if hydroelectric facilities affect the sediment transport of the rivers tested.

Statistically significant chemical changes were only found downstream of the two facilities visited multiple times. This may suggest that trends were also present at the other locations but that more rounds of sampling would have been necessary to obtain data supporting statistically significant changes. Lastly, it is of interest to note that the most dramatic changes occurred at the Paso Ancho facility, which is a "mini" facility and the second smallest facility investigated. This may support the assertion that ecological impact is not proportionate to a facility's energy generation potential. It is important to note, however, that the Paso Ancho facility was the only location at which water properties could be tested above and below not only the water intake but also the water release. Trends similar or even more pronounced than those present at Paso Ancho may have been observed downstream of the other facilities' water releases had they been tested as well.

Chiriquí Viejo Sampling

The four lower Chiriquí Viejo sites sampled were not paired directly above and directly below hydroelectric facilities and thus cannot be used to determine downstream changes below specific facilities. The observations gathered at these four sites, however, can enhance understanding of the entire river's chemical and physical dynamics and can be used as a reference point for later investigations. A downstream increase in both temperature and conductivity is present across all 8 Chiriquí Viejo sites. A downstream increase in temperature is to be expected, for the downstream sites occur at lower elevations with warmer climates and solar radiation warms river water as it flows downstream (Welch et al. 2001). The downstream increase in conductivity also aligns with expectations, for the river water at downstream sites has been in contact with bedrock for more time, allowing for greater dissolved ion weathering (Welch et al. 2001).

The lentic conditions, depth, and width of the middle two Chiriquí Viejo sites demonstrate that there was a pronounced change in the river immediately before the large El Alto and Bajo de Mina facilities that they proceed. It is interesting to note, however, that the other chemical and physical water properties of these two sites align with those observed at the other Chiriquí Viejo sites. Dissolved oxygen concentration and pH at these sites are within the range of the other sites tested, and temperature and conductivity follow the increasing trend shown by the data obtained at the other sites.

Improvements and Recommendations

A number of improvements could have been made to this study. While the field protocol used was appropriate for the majority of locations, it was likely inadequate for obtaining an accurate representation of water conditions for the second and third Chiriquí Viejo River sampling sites due to their locations on the reservoirs created by hydroelectric facilities. The lake-like nature of the river at these sites not only prohibited the acquisition of depth data by the tape measure method employed by this investigation but also calls its water sampling protocol into question. Since the water depth quickly dropped off at the edge of these reservoirs, water testing could only be performed 1 m in from the bank at each site. The chemical and physical characteristics at the shore of a lake can be very different from those near the center, so the data collected at these sites is not necessarily representative of the water properties at the entire river cross-section (Hall et al. 2003, MacIntyre and Melack 1995). This issue could be avoided in future studies by either using a boat to obtain observations near the center of these reservoirs or selecting study sites upstream of reservoirs where the river is shallow and narrow enough to permit entry by foot.

Trends in river conditions may have been more apparent if more accurate data sampling methods had been used. Considering water turbidity was below the detection limit of the turbidity tube used at all but one study site, this study could have likely benefitted from a more sensitive, spectroscopy-based method of turbidity testing. The investigation may have also benefitted from more sensitive spectroscopy-based methods for phosphate concentration testing, for all concentrations were at near the lower detection limit of the visual comparison protocol used. A water flow meter would have likely yielded more accurate water velocity and discharge results, and more river depth measurements could have been collected for each cross-section to increase the accuracy of the average river depth calculation.

Considering that some of the trends present in the Pedregalito and Paso Ancho data only became apparent after multiple days of sampling, this investigation could have been strengthened by repeated visits to all locations to gather more data points from which to draw conclusions. Water velocity data in particular was only tested once at each site, so repeated testing could have improved the confidence interval of these findings. Similarly, constraints on material availability only allowed for the one-time testing of phosphate concentration at the Paso Ancho and

Pedregalito study sites. More apparent downstream trends in phosphate concentration might have been found if this testing had been repeated multiple times at these sites and/or performed at all study locations. Since sampling at the Paso Ancho sites revealed significant water property changes below the facility's water release site, the emphasis on testing above and below only water intake points at other locations may have been a major weakness of this investigation. Ideally, observations would have been gathered above and below both the water intake and water release for each site to determine if the changes at the water release found at Paso Ancho are present elsewhere. Lastly, as with any study of this nature, the inclusion of more study sites within the study area or across a broader geographic region may have allowed for more generalized conclusions to be drawn.

Conclusion

By investigating the chemical and physical properties of rivers above and below four different hydroelectric facilities as well as four additional downstream sites on the Chiriquí Viejo River, this investigation suggested several ways in which rivers may be affected as they pass through these facilities. River discharge was significantly lower below 3 of the 4 facilities, and there were downstream changes in temperature, conductivity, pH, and the concentration of dissolved oxygen at one or more of the facilities studied. All of these properties can impact the biology, ecology, and geology of a river, so this investigation suggests that hydroelectric facilities in Chiriquí may in fact have a significant impact on various aspects of the rivers they are constructed on. Considering the rapid rate of continued hydroelectric power development in the region, further research on what these precise impacts may be is warranted. Moreover, since all facilities studied for this project have installed power generation capacities at or below 20 MW, these findings call into question the prevailing wisdom that small hydroelectric power facilities have negligible ecological effects. This subject is also deserving of further investigation, for this belief helps fuel hydroelectric power development in Panama and around the world.

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